Longitudinal Control Strategy Investigation for Coaxial Compound Helicopters

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ABSTRACT

The coaxial compound helicopters have obtained a lot of research interest due to their outstanding performance, especially in high speed flight. This rotorcraft could use the longitudinal cyclic pitch and the elevator to control the pitching moment during the flight. In order to investigate the effect of different longitudinal control strategy on the flight dynamics characteristics of this helicopter, a validated flight dynamics model is utilized to calculate the control derivatives, the bandwidth and phase delay, the attitude quickness, and the control inputs and pilot workload during the Pull-up & Push-over manoeuvre. The results indicate that control power of the longitudinal cyclic pitch is higher than that of the elevator, especially in hover and low speed forward flight due to the lack of the dynamic pressure on the elevator. The bandwidth and phase delay results demonstrate that both longitudinal control strategy could attain satisfactory small-amplitude response characteristics, and the attitude quickness results show that the helicopter capability in moderate to large control response is relatively high due to the additional damping provided by the rigid rotor. The manoeuvre simulation results indicate that using reasonable allocation between the longitudinal cyclic pitch and elevator is an efficient method to reduce the pilot workload and the maximum power consumption during manoeuvring flight.

NOTATION

n_z	= normal load factor
p,q,r	= angular velocities in body axes (*rad/s*)
u,v,w	= translational velocities in body axes (*m/s*)
$\boldsymbol{u}$	= control vector
$\boldsymbol{x}$	= the state vector
A	= system matrix
B	= control matrix
M_q	= pitching damping (*rad/s*)
R	= rotor radius (*m*)
V	= forward speed (*m/s*)
ϕ,θ,ψ	= Euler angle (*rad*)
γ	= glideslope angle (*rad*)
χ	= track angle (*rad*)
β_e	= elevator deflection (*rad*)
θ_0	= collective pitch (*deg*)
θ_{1c}	= lateral cyclic pitch (*deg*)
θ_{1s}	= longitudinal cyclic pitch (*deg*)
θ_{01}	= collective pitch differential (*deg*)
θ_{con}	= longitudinal control input (*deg*)

INTRODUCTION

Coaxial compound helicopters have been proposed as a future rotorcraft configuration. Research has shown that this helicopter configuration has improved performance in high speed flight[1, 2]. In this flight regime, novel control methods, such as the elevator, can be utilized to improve the flight dynamics characteristics of this helicopter.

The helicopter usually uses the longitudinal cyclic pitch to control the tilt angle of rotor disc, and consequently change the pitch attitude. However, the maximum flight speed of the coaxial compound helicopter is significantly higher than the conventional helicopter, and the dynamic pressure of the tailplane is sufficient in high speed flight, which makes the use of the elevator become possible. Using the elevator would not influence the aerodynamic characteristics of the coaxial rotor, which would guarantee the rotor efficiency at various flight ranges, and decrease the power consumption in both trimmed and manoeuvre flight. However, the control power of the elevator is relatively low in hover and low speed forward flight due to the lack of the dynamic pressure. Therefore, with the aim to improve the flight dynamics characteristics of the coaxial compound helicopter, it is necessary to assess its longitudinal control strategy between longitudinal cyclic pitch and elevator in both trimmed and manoeuvre flight.

There has been much research into the coaxial compound helicopter in recent years due to its high-speed performance[3]. At the higher end of the speed range, both the longitudinal cyclic pitch and the elevator deflection can potentially be used to provide pitching control moment [4]. The control power of the cyclic pitch for a coaxial rotor is much greater compared with other helicopters due to the higher flapping frequency of its rigid rotor[5]. Therefore, the longitudinal control strategy for coaxial compound helicopters is different from conventional helicopters and requires careful consideration. In the development of the XH-59A coaxial compound helicopter, an all-moving tailplane was utilized to offload the rotor in trimmed flight [4] and the use of an elevator was tested during the development of the X2TD coaxial compound helicopter [6].

In light of the preceding discussion, this paper uses a validated flight dynamics model of the coaxial compound helicopter to investigate control and maneuver characteristics using various longitudinal control strategies. The control derivative, the bandwidth and phase delay, and the attitude quickness are assessed with longitudinal cyclic pitch and the elevator deflection, respectively. Then, a combined longitudinal control strategy is proposed to improve coaxial compound helicopter flight dynamics characteristics, especially in maneuvering flight. This strategy is evaluated with the Pull-up & Push-over Mission-Task-Element (MTE), in which the pilot workload is also investigated with a time-domain assessment metrics method.

MODEL OVERVIEW

The flight dynamics model of the coaxial compound helicopter used in this investigation are based on XH-59A helicopter, and has been validated with existing flight test and simulation results[7]. This model consists of the aerodynamic model of the coaxial rigid rotor, fuselage, horizontal tail, vertical tail, and propeller.

In the coaxial rigid rotor aerodynamic model, Pitt-Peters dynamic inflow representation is used to determine the induced velocity distribution, and the model assumes that the lower rotor does not influence the induced velocity at the upper rotor. The rotors are assumed to be sufficiently close together that the induced velocity on the lower rotor is equal to the sum of the induced velocity on the upper and lower rotors. Meanwhile, the combination of the equivalent flapping offset and spring is introduced in the rotor model to simulate the flapping characteristics of rigid rotors.

The fuselage model is based on wind tunnel data [8], and 2-D representations of the horizontal and vertical tails with strip theory are incorporated into the model. The lift and drag coefficients can be obtained from 2-D airfoil aerodynamics look-up tables with given angle of attack and sideslip. In order to take the effect of the elevator into consideration, the aerodynamic model of the elevator is added in the model of the horizontal tail, which is in line with reference [9]. The modelling process of the propeller is similar with the rotor, except that the flapping effect is excluded in the propeller model.

Therefore, the flight dynamics model of the coaxial compound helicopter can be expressed using state-space form:

$$\dot{\boldsymbol{x}} = f(\boldsymbol{x}, \boldsymbol{u}, t) \tag{1}$$

where: $\boldsymbol{x}$ is the state vector; $\boldsymbol{u}$ is the control vector; t is time. The state vector of the coaxial compound helicopter $\boldsymbol{x}$ contains 24 elements, which are the translational velocities, angular velocities, the Euler angles of the helicopter, the flapping angles of the upper and lower rotors; the induced velocities of the upper rotor, lower rotor, and the propeller. The control vector $\boldsymbol{u}$ includes the conventional control inputs of the helicopter, such as the collective pitch, the longitudinal and lateral cyclic pitches, and the differential collective. It also contains the unique control inputs of the coaxial compound helicopter, which are the propeller collective and the elevator deflection.

With the aim to investigate the controllability and handling qualities of the helicopter, the state-space equation of the helicopter can be linearized as:

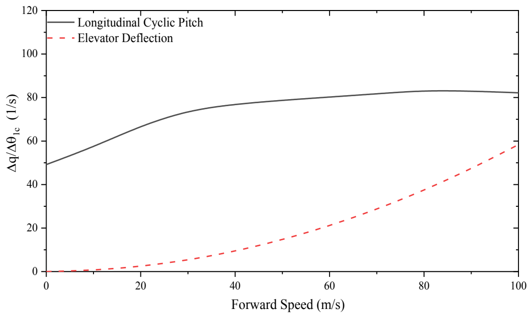
$$\dot{\boldsymbol{x}}_{linear} = A\boldsymbol{x}_{linear} + B\boldsymbol{u}_{linear} \tag{2}$$

where: $\boldsymbol{x}_{linear} = [u, v, w, p, q, r, \phi, \theta]^T$ is the state vector in linearization; $\boldsymbol{u}_{linear} = [\theta_0, \theta_{1c}, \theta_{1s}, \theta_{01}, \beta_e]^T$ is the control vector in linearization in this article. The state and control vectors are perturbations from the trimmed state. The system matrix, A, contains the stability derivatives whereas the control derivatives define the control matrix, B.

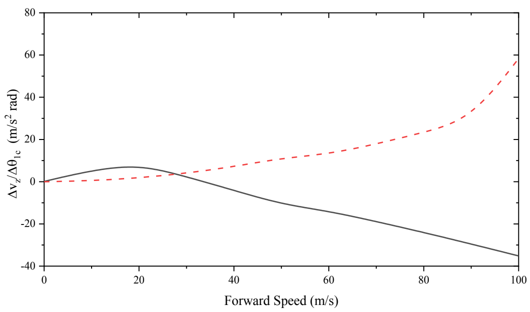
CONTROLLABILITY

Control Derivatives

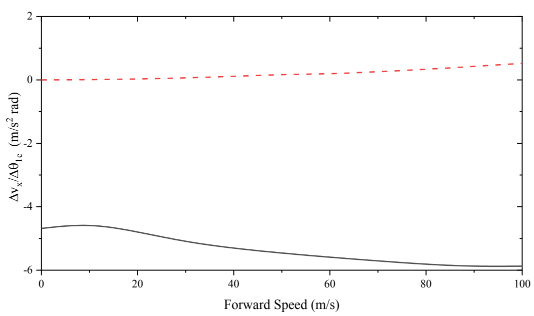
Figure 1 shows the pitch rate, vertical velocity and forward velocity derivatives with respect to longitudinal cyclic pitch and elevator control inputs with respect to the flight speed.



(a) Pitch Rate Control Derivative



(b) Vertical Velocity Derivative



(c) Forward Velocity Derivative

Figure. 1 The pitching control derivatives

As indicated in Figure. 1 (a), the pitch rate control derivative with respect to longitudinal cyclic is relatively low in hover and low speed forward flight due to the effect of the aerodynamic interference. However, this control derivative is still much higher than for the conventional helicopter across the flight range due to the higher flapping rigidity of the coaxial rotor [7]. On the other hand, the pitching control derivative of the elevator deflection increases with the forward speed. This control derivative is dependent on the dynamic pressure on the horizontal tail. In hover and low speed forward flight, the elevator clearly cannot provide sufficient control power. When the forward speed is above 60 m/s, although the control power provided by the elevator deflection is still lower than the longitudinal cyclic pitch, this value is similar with other helicopters [8].

Figure 1 (b) and Figure 1 (c) indicate that the longitudinal control strategies change the forward and vertical acceleration to a large extent. The longitudinal cyclic pitch would significantly influence vertical and forward forces because it causes the tip path plane to tilt in longitudinal direction, which changes the direction of the rotor thrust. The elevator deflection only slightly influences the vertical acceleration results as elevator deflection alters the thrust provided by the horizontal tail, which in turn affects the overall vertical force.

In short, the longitudinal cyclic pitch could provide more control power compared to other helicopters, and the control derivative provided by the elevator is relatively low in hover and low speed forward flight, but it is improved in high speed flight. Moreover, the control strategies also influence the forward and vertical forces differently.

Bandwidth and Phase Delay

In order to assess the influence of the longitudinal control strategies on handling qualities, the small-amplitude response requirement (bandwidth & phase delay) is analyzed with longitudinal cyclic pitch and elevator deflection. The bandwidth and phase delay can be used to evaluate the handling qualities in small amplitude control response. To obtain the bandwidth and phase delay in the longitudinal channel, dynamic models of the control mechanism and the actuator are added [9]. Their transfer functions used are shown below:

$$S_{Control} = \frac{16.9747}{s^2 + 44.4s + 986} \tag{3}$$

$$S_{Actuator} = \frac{1}{0.02s + 1} \tag{4}$$

where: $S_{Control}$ is the dynamic model of the control mechanism; $S_{Actuator}$ is the dynamic model of the actuator. Thus, the bandwidth and phase delay results with longitudinal cyclic pitch and elevator deflection in various speeds are shown in Table. 1. Also, handling qualities ratings are added in this table according to ADS-33E-PRF.

As illustrated in Table. 1, at low speed there are significant differences (and therefore ratings) between longitudinal cyclic and elevator control strategies. This difference diminishes as forward speed increases, and at the higher speed range there is little difference between the results for both strategies. Using the elevator deflection would degrade the ratings in low speed forward flight due to the lack of the control power. As the forward speed increases, the results are significantly improved and returned to Level 1 when the forward speed is above 60 m/s. With the longitudinal cyclic pitch, the bandwidth and phase delay are also degraded in hover because of the aerodynamic interference in the coaxial rotor system.

Table. 1 Bandwidth and Phase Delay

Velocity (m/s)	Longitudinal Cyclic Pitch			Elevator Deflection		
	Bandwidth	Phase Delay	Ratings	Bandwidth	Phase Delay	Ratings
0	2.47	0.06	Level 2	-	-	-
20	3.33	0.05	Level 1	0.45	0.05	Level 3
40	3.96	0.05	Level 1	1.01	0.05	Level 2
60	4.89	0.05	Level 1	2.27	0.05	Level 1
80	5.73	0.05	Level 1	3.98	0.05	Level 1
100	7.26	0.05	Level 1	5.79	0.05	Level 1

Attitude Quickness

The attitude quickness is a requirement to assess the helicopter capability in moderate to large control response. The attitude quickness results with both longitudinal control strategies are shown in Table.2. It should be mentioned that the value of the $\Delta\theta_{\min}$ in the evaluation is around 10 degrees. Meanwhile, due to the lack of the requirement of the pitching attitude quickness in forward flight, the related data in reference 8 is used to evaluate the pitching attitude quickness of this helicopter, which demonstrates this helicopter has outstanding attitude quickness compared with other helicopters.

Table. 2 Attitude Quickness

Velocity (m/s)	Longitudinal Cyclic Pitch	Elevator Deflection
0	2.625	-
20	3.200	2.733
40	3.624	3.556
60	3.893	3.667
80	3.437	3.413
100	3.125	3.051

The pitching attitude quickness can be simplified as a first-order system, which is:

$$\dot{q} - M_q q = M_{\theta_{1s}}\theta_{\mathrm{con}} = -M_q q_s \theta_{\mathrm{con}} \tag{5}$$

where: $M_{\theta_{1s}}$ is the control derivatives of the longitudinal cyclic pitch; θ_{con} is the longitudinal control input. Based on Eq. (5), when there is a pulse input in longitudinal cyclic pitch, the pitching angular velocity and pitching attitude can be expressed as:

$$\begin{aligned} & t \le t_1 : q = q_s(1 - e^{M_q t})\theta_{1s}, \\ & \theta = \frac{q_s}{M_q}(1 + M_q t - e^{M_q t})\theta_{1s} \end{aligned} \tag{6}$$

$$\begin{aligned} & t > t_1 : q = q_s e^{M_q t}(e^{-M_q t} - 1)\theta_{1s}, \\ & \theta = \theta(t_1) - \frac{q_s}{M_q}(e^{M_q t_1} - 1)(e^{M_q (t - t_1)} - 1)\theta_{1s} \end{aligned} \tag{7}$$

According to Eqns. (6-7), the pitching attitude quickness can be seen as:

$$\frac{q_{pk}}{\Delta\theta_{pk}} = -\frac{M_p}{\hat{t}_1}(1 - e^{-\hat{t}_1}) \tag{8}$$

where: $\hat{t}_1 = -M_q t_1$, and t_1 is the duration of the pulse. When $t_1 \to 0$, the pitching attitude quickness is $q_{pk} / \Delta\theta_{pk} \to M_q$.

In addition, the rigidity of the coaxial rotor is much higher than other rotor configuration, leading to the increase of the pitching damping, and consequently improve the attitude quickness results across the flight range. In addition, with both control strategies, the pitching damping is nearly invariable. Therefore, the attitude quickness is almost independent from the control strategy adopted as shown in Table.2.

LONGITUDINAL CONTROL STRATEGY

Based on the analysis above, only using elevator deflection will not provide sufficient control power to guarantee the maneuverability of the coaxial compound helicopter. However, the elevator deflection can be used to supplement longitudinal cyclic control to improve the maneuverability of the coaxial compound helicopter in high speed flight. In this article, the following strategy is proposed:

$$\begin{cases} \theta_{1s} = \theta_{\mathrm{con}} \\ \beta_e = -aV^2\theta_{\mathrm{con}} \end{cases} \tag{9}$$

where β_e is the elevator deflection; V represents the forward speed; θ_{1s} donates the longitudinal cyclic pitch; a is the elevator deflection control parameter. During hover and low speed forward speed, the elevator deflection is not utilized in the longitudinal control strategy as the control derivative of the elevator deflection is low in this flight range. The change in elevator deflection could also produce additional power consumption, and consequently β_e should be close to zero at this flight range. In high speed flight, the elevator deflection can be imposed to improve the aggressiveness characteristics of the coaxial compound helicopter in maneuvering flight. Therefore, the value of the factor a should increase with the forward speed. Meanwhile, the strategy should keep the elevator away from the stall condition across the flight regime. Thus, with the consideration of its aerodynamic characteristics, the factor a is set to be 0.0001.

Inverse Simulation Method

Inverse simulation is a useful method to analyze the manoeuvrability of the helicopter. The basic theory and algorithm have been illustrated in reference [10].

In this article, the forward time response method is used based on the flight dynamics model. Therefore, the inverse simulation can be represented as a "trim process" in each time steps through the manoeuvre. At every time step, the control input must be varied to ensure the correct flight path, which is given by the mathematical description of the Mission-Task-Element (MTE).

Pull up & Push over Mathematical Description

The Pull-up & Push-over Mission-Task-Element (MTE) defined by the ADS-33E-PRF is used in this article to assess the maneuverability with the control strategy given by Eq. (9).

During the Pull-up & Push-over MTE, the helicopter starts at the trimmed condition, and the flight speed is 120kt (approximately 60m/s). Then, the normal load of the coaxial rotor n_z of the helicopter needs to follow the trajectory of Figure. 2, according to the Level 1 requirement in ADS-33E-PRF.

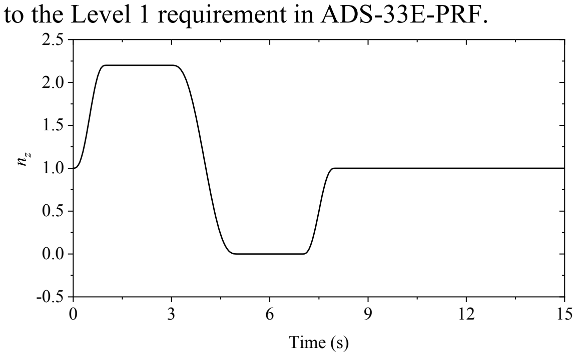


Figure. 2 Load factors throughout the Pull-up & Push-over MTE

Based on Figure 2 and reference [11], the mathematical description of this MTE is shown below:

$$\dot{\gamma}=\frac{\dot{V}\dot{z}-Vg(1-n_z)}{V^2\cos\gamma} \tag{10}$$

$$\dot{V}=-g\sin\gamma \tag{11}$$

$$\chi=0 \tag{12}$$

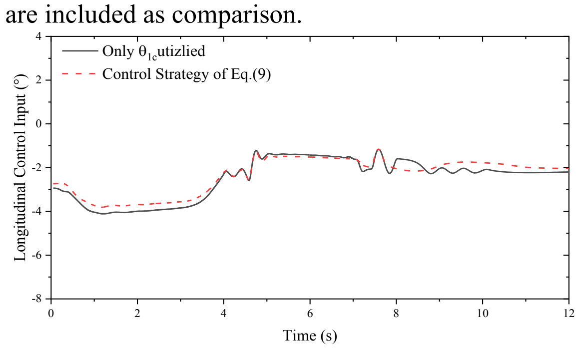
$$\dot{\psi}=0 \tag{13}$$

where: γ is glideslope angle; n_z is the normal load of the coaxial rotor; χ is the track angle; and ψ is the heading angle.

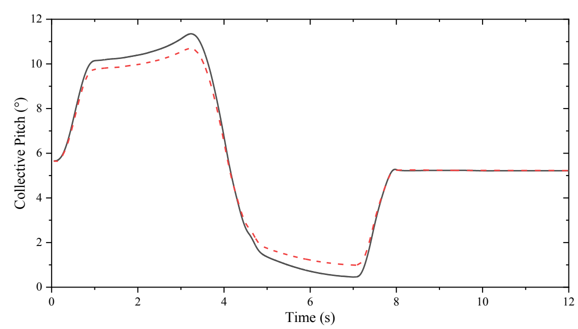
The maximum normal load of the coaxial rigid rotor utilized in this investigation is 2.2 [12]. Therefore, this load factor distribution along the time can be expressed using fifth-order polynomials. The polynomial should guarantee the value of the load factor at every time points satisfies the requirement and the transition across the manoeuvre will be smooth.

Results and Analysis

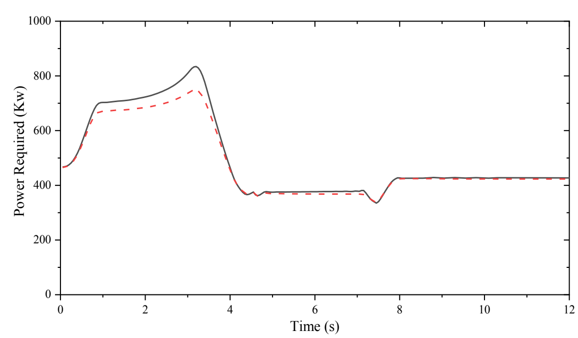
In this assessment, the inverse simulation method is used to calculate the control input of the coaxial compound helicopter during the maneuver. The control input results (longitudinal cyclic pitch and collective pitch) and power consumption during the maneuver are shown in Figure. 3. Also, the control input results only using the longitudinal cyclic pitch are included as comparison.



(a) Longitudinal control input



(b) Collective pitch



(c) Power consumption

Figure. 3 The control inputs and power required during the Pull-up & Push-over MTE

Table. 3 Pilot Workload Metrics

Pilot Workload Metrics	Control Strategy of Eq. (3)		Only Longitudinal Cyclic pitch used	
	Aggressiveness	Duty cycle	Aggressiveness	Duty cycle
Longitudinal control	3.84 %	0.833	3.96 %	1.333
Collective pitch	8.87 %	0.417	9.21 %	0.417

Fig. 3 indicates that both control strategies could achieve the Pull-up & Push-over MTE within the Level 1 time limit. Moreover, the longitudinal control strategy has an influence on the control inputs and power required during the Push-up & Pull-over MTE.

The amplitude of the longitudinal cyclic pitch is reduced with the adoption of Eq. (9) because additional control power is provided by the elevator deflection. In addition, the longitudinal control strategy also affects the collective pitch input. From Fig 1. (b), using the elevator deflection would change the lift provided by the horizontal tail, and therefore, the collective pitch is also changed during this maneuver. Moreover, the extra lift of the horizontal tail would reduce the overall power consumption, especially when the collective pitch is relatively high (from 2s to 4s in Figure. 3). In this flight range, the aerodynamic efficiency of the coaxial rotor decreases and the use of the elevator deflection would partly offload the coaxial rotor and improve the helicopter performance. Thus, the maximum transient power required is reduced with the strategy of Eq. (9), which could further increase the capability of this helicopter in high speed flight.

To better assess the pilot workload during the MTE, a series of time-domain pilot workload metrics can be used, which include the aggressiveness and duty cycle indices. Information on these metrics are given in reference [13]. Aggressiveness parameter is a measure of control deflection magnitude from the trim control input position during the MTE, and the duty cycle is a measure of the frequency of the adjustment change across the MTE manoeuver. The pilot workload results are shown in Table. 3.

According to Table. 3, the longitudinal control strategy proposed in this article could decrease the pilot workload during the maneuver. As indicated in Figure 3. (a), the oscillation of longitudinal control input is less using the strategy given by Eq. (9) during the time ranging from 8s to 10s. Based on the flapping features of the rotor, the input of the collective pitch also induces additional pitching hub moment to the coaxial compound helicopter, which would couple with the longitudinal control input. Therefore, the use of the elevator deflection would alleviate this effect and consequently reduce the pilot workload during the MTE.

CONCLUSIONS

The longitudinal control strategies, including the longitudinal cyclic pitch and the elevator deflection, are investigated for a coaxial compound helicopter. The control derivatives, the bandwidth and phase delay, and the attitude quickness are analyzed with different control strategies. Then, a combined longitudinal control strategy for the coaxial compound helicopter is proposed, and the Push-up & Pull-over MTE are used to assess this strategy. The results allow the following conclusion to be drawn:

1) The control derivatives correspond to longitudinal cyclic pitch are much higher across the speed range due to the higher flapping frequency of the coaxial rigid rotor. Using longitudinal cyclic pitch, the helicopter could have satisfactory small-amplitude response ratings and the attitude quickness.
2) The control derivatives related to the elevator deflection increase with the forward speed, and the bandwidth and phase delay ratings are degraded in hover and low speed states because of the lack of control power. The attitude quickness values are still satisfactory across the flight range.
3) A longitudinal control strategy for the coaxial compound helicopter is proposed in this article to combine both the longitudinal cyclic pitch and the elevator deflection to improve the maneuverability. The Push-up & Pull-over MTE simulation results indicate that this strategy could decrease the pilot workload and the maximum transient power required during this MTE.

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